SN neutrino theory: technology overview

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Imagine designing a wild intensity frontier experiment

- Let's dream! What if we could:

  - Take ~3×10^{29} kg of matter and convert it to pure energy, in the form of 10^{58} neutrinos with energies of 10^7 eV.

  - Create a ball of matter so dense (10^{12}–10^{14} g/cm^3, nuclear densities) that it is be opaque even for neutrinos. Measure its cooling properties as a function of time.

  - Create a dense neutrino gas (10^8–10^{10} moles of neutrinos/cm^3). Let this system expand. Measure the resulting collective flavor oscillation dynamics.

This experiment is carried out in a core-collapse supernova!

- Inner ~ 1.4 $M_\odot$ of material collapses to a super-dense object just a few tens of km across

- Gravitational binding energy of the collapsed core, $\sim GM^2/R$, equals to about 10% of its rest mass

- It is emitted in 10^{58} neutrinos in a burst lasting $\delta t \sim$ seconds

    - Neutrino diffusion time scale

- At ~ 100 km, the number density of streaming neutrinos is

    - $\sim 10^{58}/4\pi r^2 c\delta t \sim 10^{32}$ cm^{-3}

    - Comparable to the number density of matter

Evolution of the explosion is reflected in neutrinos

- Neutronization burst, accretion and cooling phases can all be seen in neutrinos

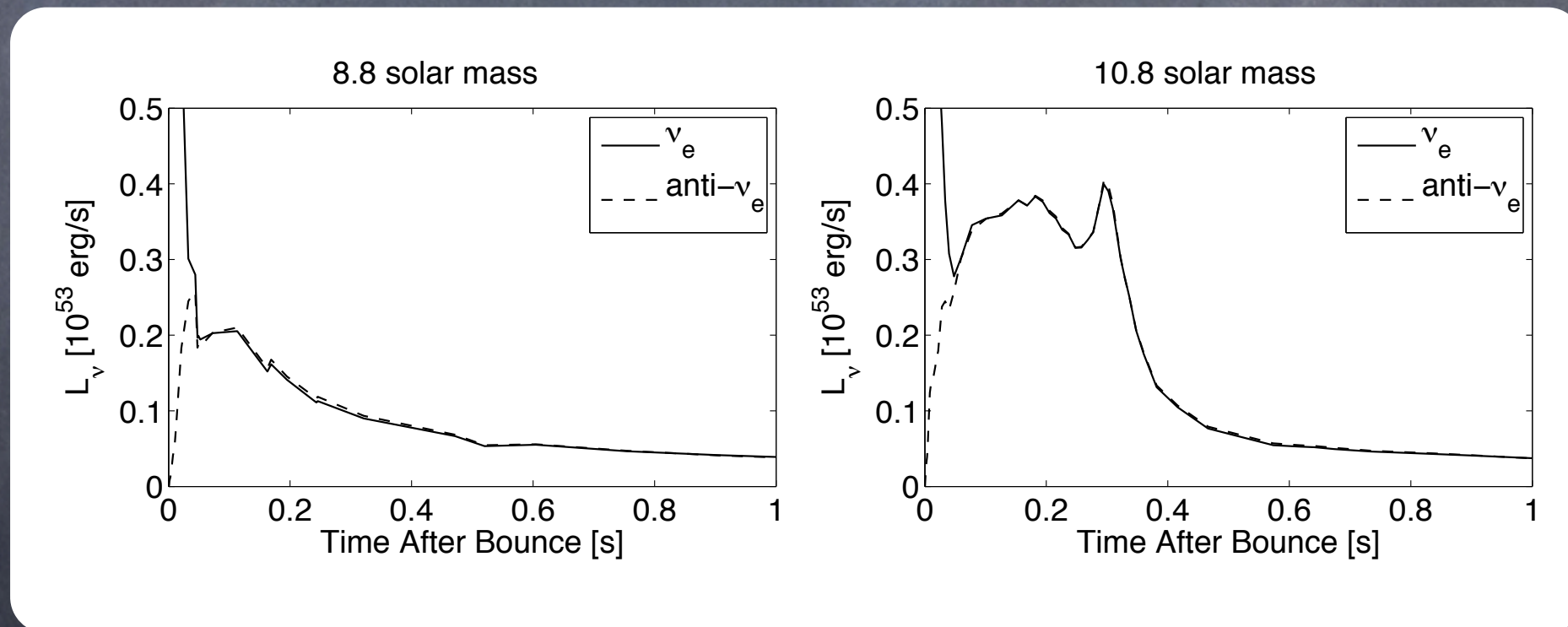- Importantly, different for different progenitor masses

Fig from Fischer, Whitehouse, Mezzacappa, Thielemann, Liebendörfer, arXiv:0908.1871

Measure each of the phases

- The **Neutronization burst** provides information about the onset of the explosion, shock breakout through the neutrinosphere; also, a useful sharp time structure

- During the **Accretion stage** the shock stalls at a few hundred km; we need to know when and how it is reenergized

    - 50-year question in SN theory!

- **Cooling stage** ends with the formation of a neutron star or a black hole. The signal is sensitive to new physics contributions to cooling (light hidden sector!). Monitor how the shock travels out and the turbulent bubble behind expands.

    - May be possible thanks to neutrino oscillations!

Cooling bounds on new physics

- Two dozen neutrinos observed from 1987A confirmed the rough picture of core-collapse supernovae as gravity-powered neutrino bombs

- This limited dataset already provides some of the best known constraints on many classes of new physics models with light, weakly interacting degrees of freedom

  - nonstandard neutrinos, axions, KK gravitons, extra-dim photons/unparticles, dark photons ...

- If this can be done with ~20 events, how about thousands of events expected from the next Galactic SN?

Once-in-a-lifetime opportunity

- The next SN likely to give

    - 10^4 electron antineutrinos at SK (10^5 at HyperK)

        - plus hundreds (thousands) of nu-e elastic scattering events

    - several thousand electron neutrinos at "(E)LBNE/F", potentially with good energy resolution

    - <u>Second-by-second</u> evolution of the spectra

Gold mine of physics information

- Cooling curves carry information about neutrino trapping, dynamics of the explosion, state of nuclear matter in the center, equation of state as a function of density, new physics contributions to energy transport ...

- Nature does not seem to know or care about the separation between the different DOE offices!

Theory required part of "technology"!

- For example, let's say we would like to measure the total energy release

  - Energy is released in neutrinos and antineutrinos of **all flavors**

  - Just measuring nu-e-bar's is not enough

  - Measuring of neutral current rate helps, but also not enough, if the spectrum of nu-x is unknown

- Fortunately, neutrinos oscillate. If we can understand the oscillation pattern, we can infer the total energy released, second-by-second

The richest and most challenging neutrino oscillations problem known

- Possible matter effect in the Earth

- "Solar" MSW in the outer envelope of the progenitor

- "Atmospheric" MSW in the outer envelope of the progenitor

- Turbulent region behind the shock

- Collective oscillations near the neutrino-sphere

- This is schematic, the order of some of these ingredients could be interchanged, depending on the progenitor mass, stage of the explosion

Earth effect

- The density of the Earth is close to resonant for the "solar" splitting and 20-40 MeV SN neutrinos

    - cf. the D/N effect in ^{8}B solar neutrinos is expected at high energies

- Can help to distinguish between different mixing scenarios

- See, e.g.,

    - Smirnov, Spergel & Bahcall, PRD 1994

    - Lunardini & Smirnov, arXiv:hep-ph/0009356

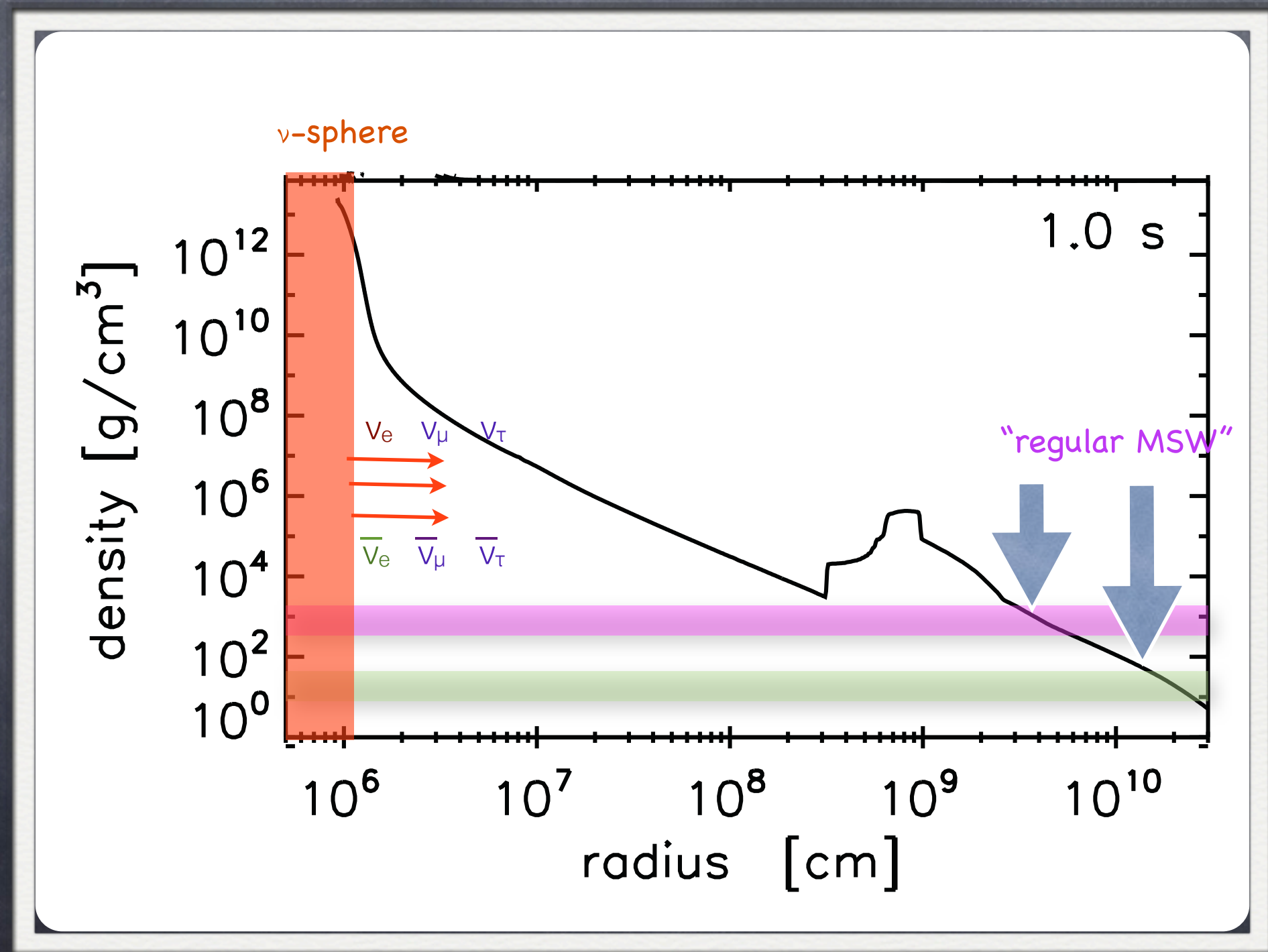   - Dighe, Kachelriess, Raffelt & Tomas, arXiv:hep-ph/0311172

Sun: 2-state oscillations

$$P_2(\nu_e \to \nu_e) = \sin^2\theta \sin^2\theta_\odot + \cos^2\theta \cos^2\theta_\odot$$
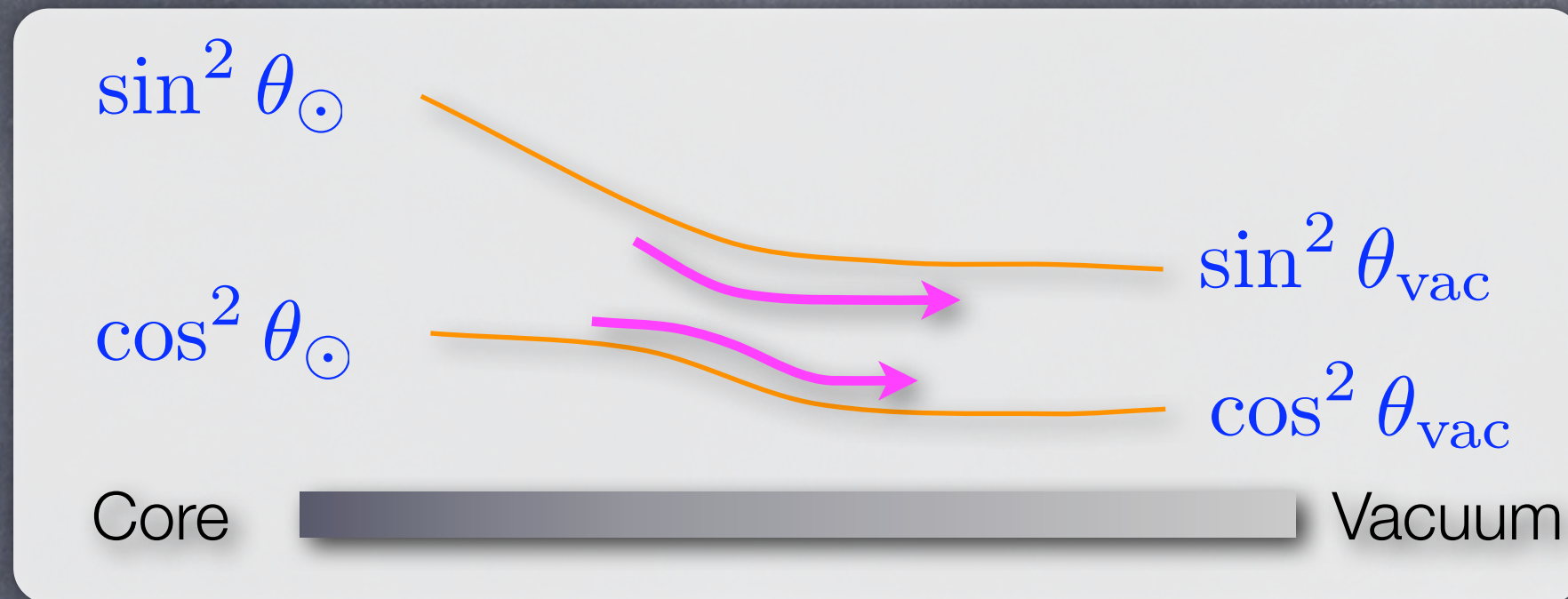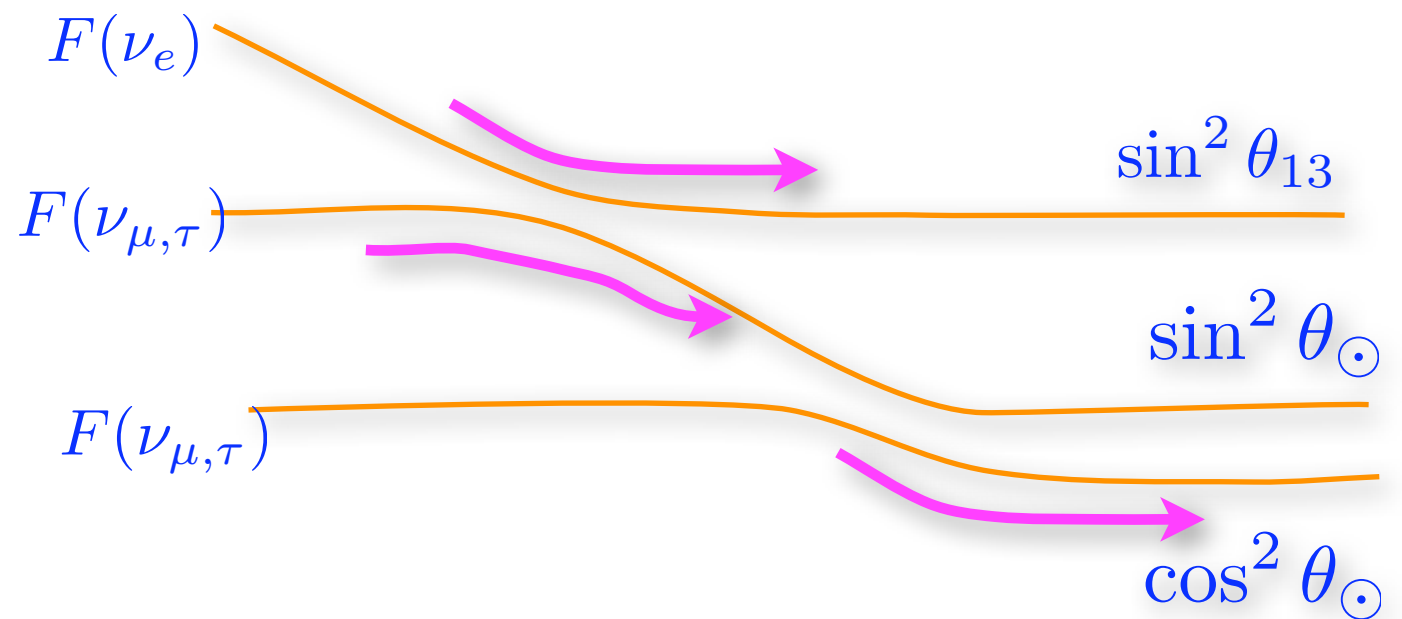

- The evolution is adiabatic (no level jumping), since $l_{osc} \ll$ density scale height ($|d \ln\rho/dr|^{-1}$)

  - Hint: for most of the Sun, the density scale height is $R_{sun}/10$, while l_{osc} is comparable to the width of Japan (KamLAND)

# SN ν oscillations: 2 MSW densities

SN MSW transformations, schematics

- Given the scale height in the progenitor, the evolution is very adiabatic

  - the adiabaticity of the atmospheric resonance is controlled by theta13

- Prediction for the nue signal during the **neutronization burst** is critically dependent on the sign of MH

$F(\nu_e)$

$F(\nu_{\mu,\tau})$

$F(\nu_{\mu,\tau})$

$\sin^2 \theta_{13}$

$\sin^2 \theta_\odot$

$\cos^2 \theta_\odot$

$F(\nu_{\mu,\tau})$

$F(\nu_{\mu,\tau})$

$F(\bar{\bar{\nu}}_e)$

$\sin^2 \theta_{13}$

$\sin^2 \theta_\odot$

$\cos^2 \theta_\odot$
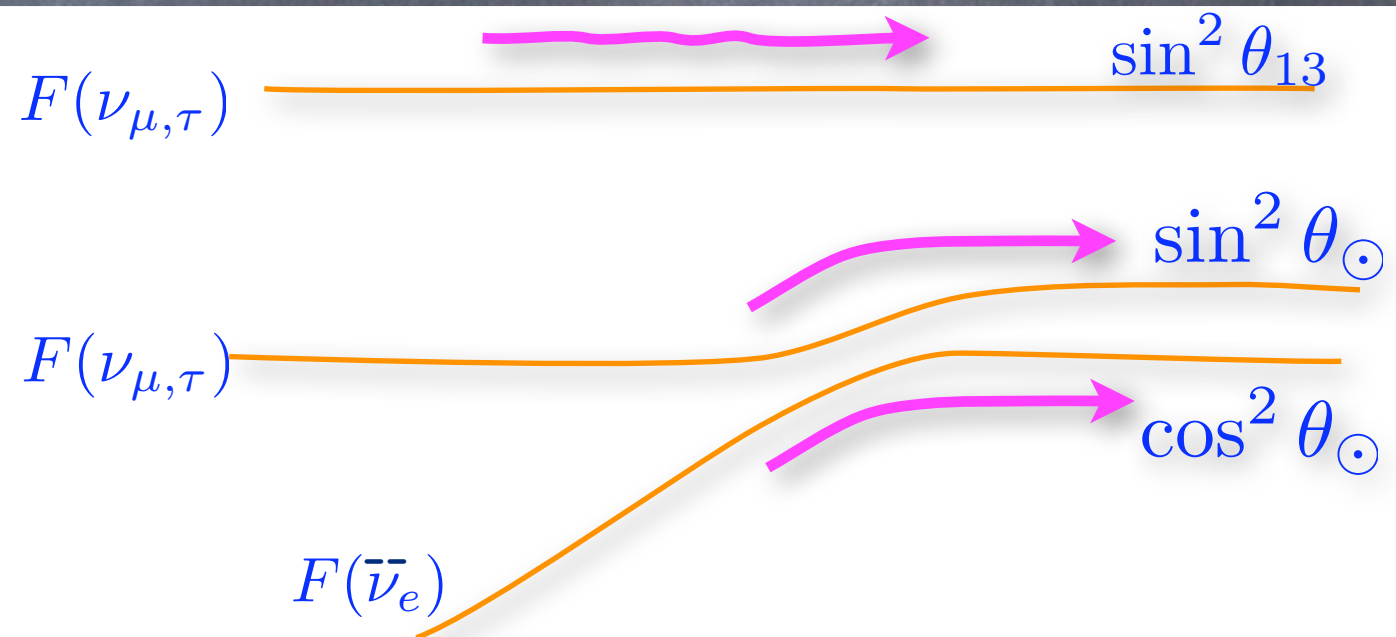
For inverted hierarchy, the same happens in antineutrinos.

# Dynamical density profile
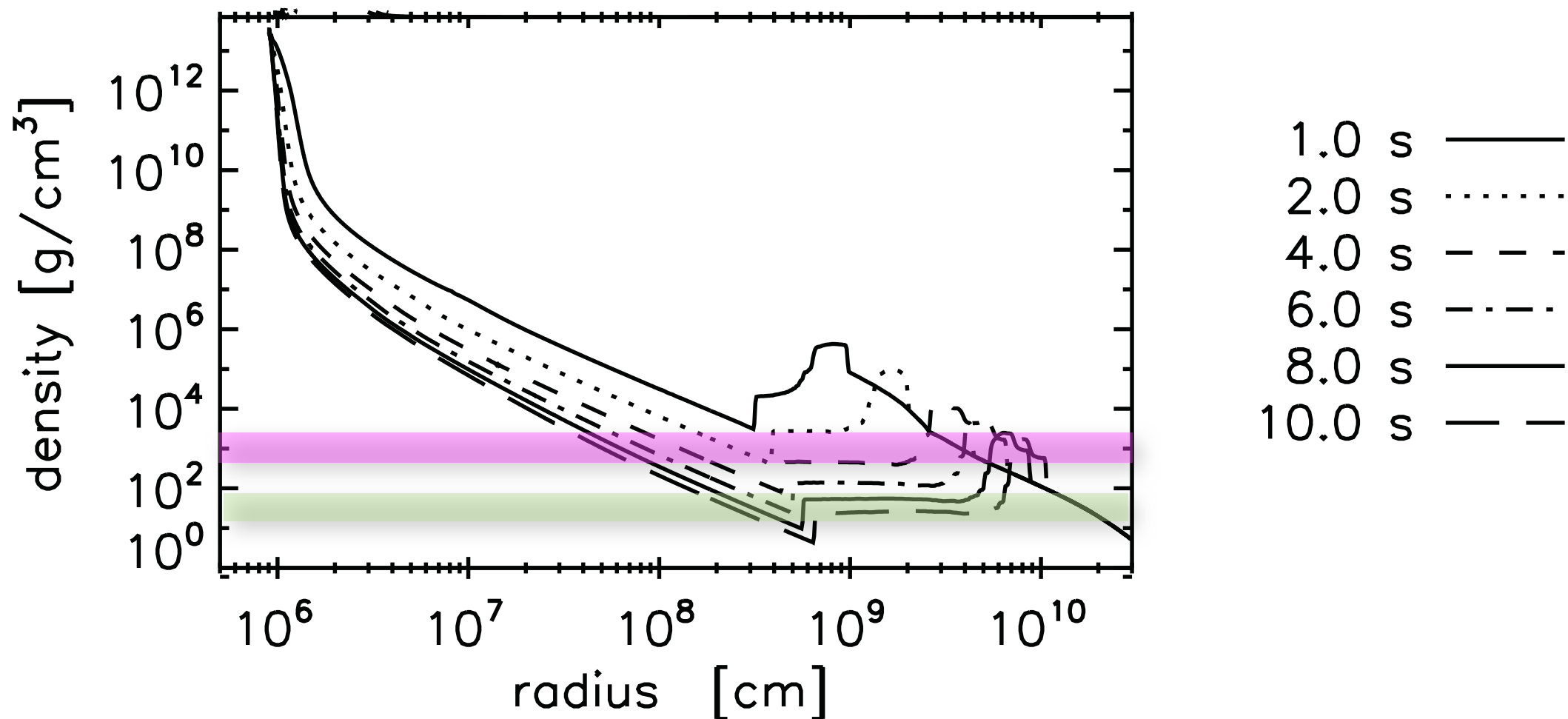
- Front shock reaches the regions where "atmospheric" and "solar" transformations happen, while neutrinos are being emitted

  - See Schirato & Fuller (2002)   astro-ph/0205390

Moving shock and MSW transformations

→ The shock is infinitely sharp from the neutrinos' point of view (photon mean free path).

→ When it arrives at the resonance, the evolution becomes non-adiabatic.
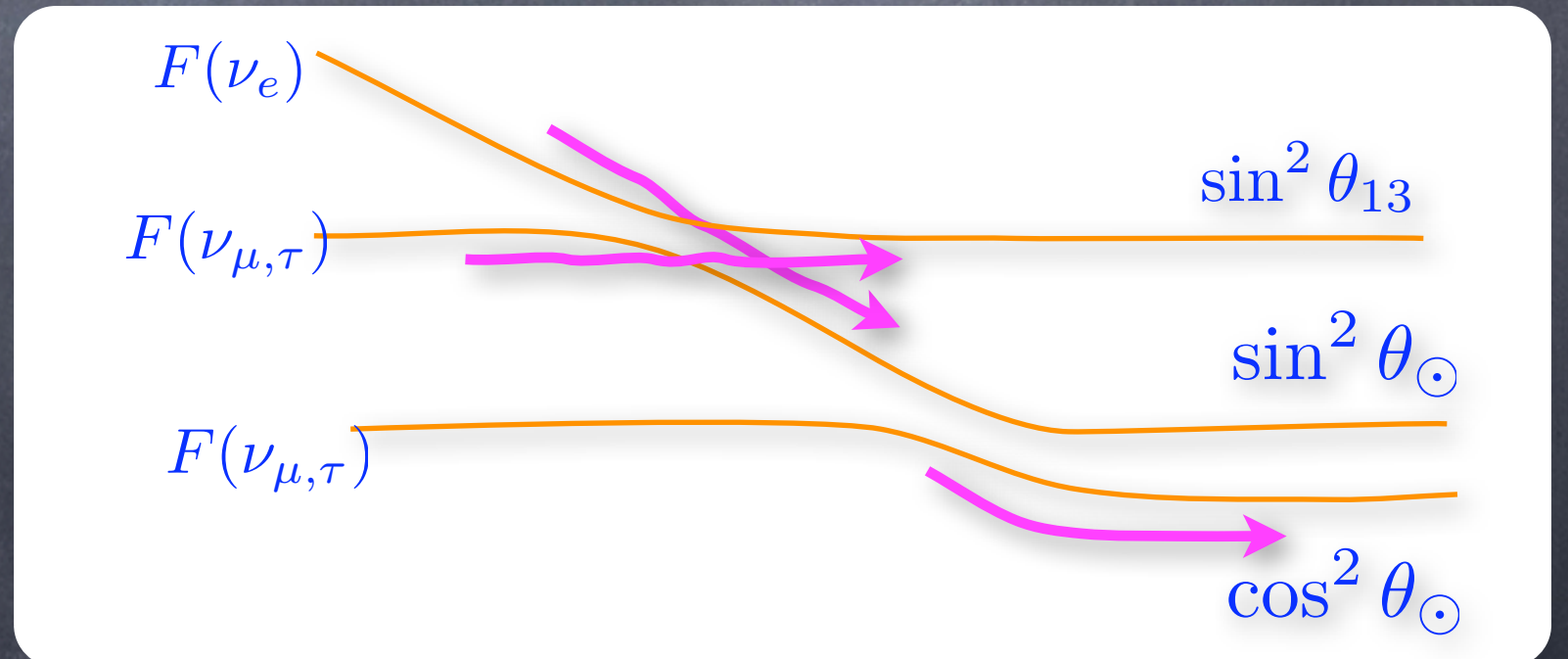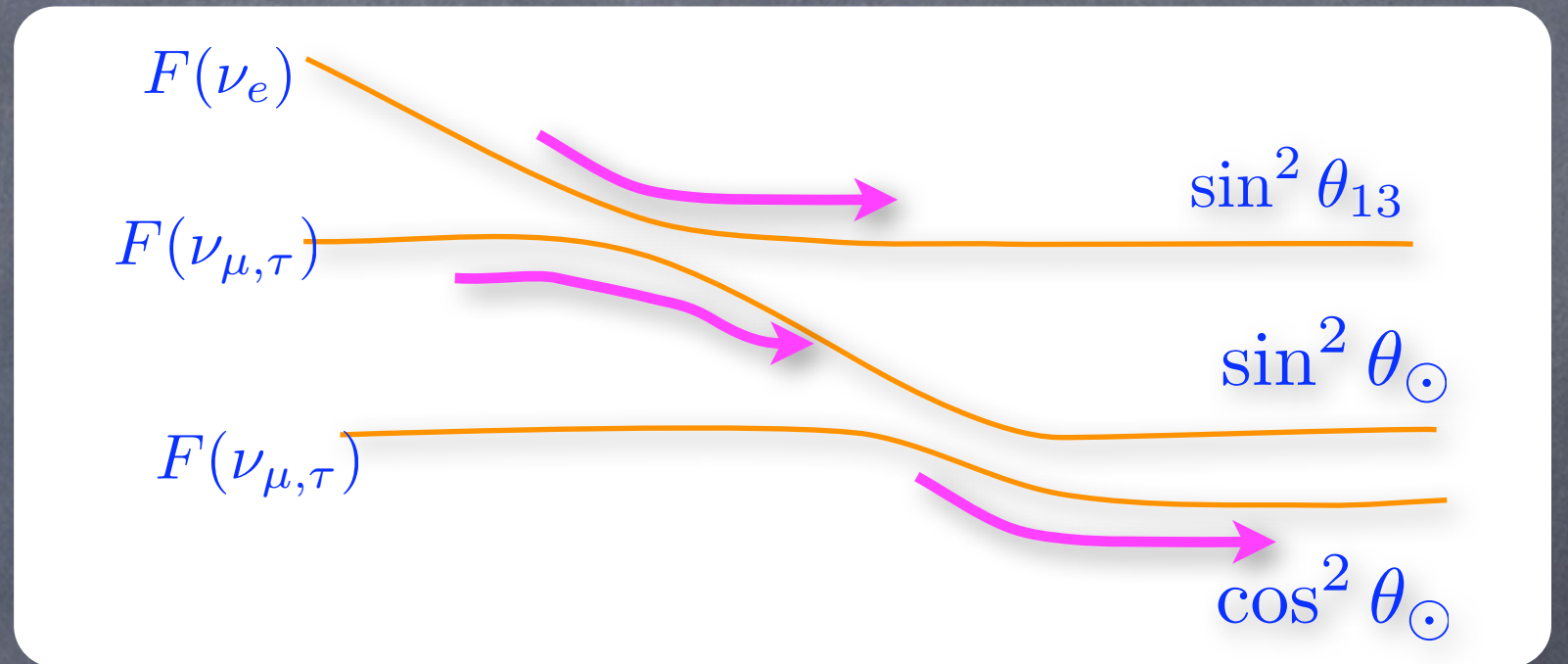
For inverted hierarchy, the same happens in antineutrinos.

3D simulations show turbulence

- 3d simulations of the accretion shock instability Blondin, Mezzacappa, & DeMarino (2002)

- See http:// www.phy.ornl.gov/tsi/ pages/simulations.html

- extensive, well-developed turbulence behind the shock
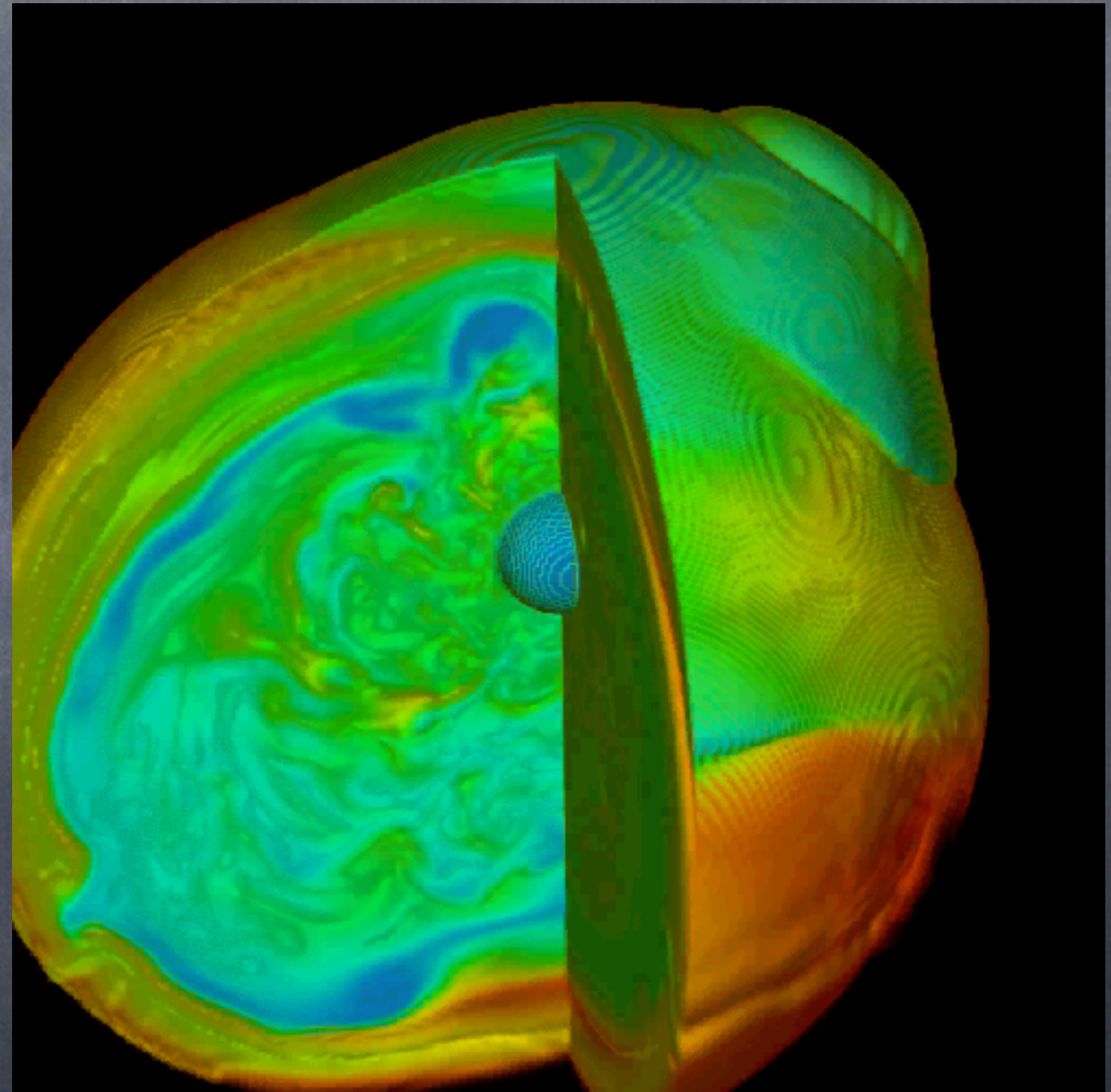
Turbulence makes neutrinos diffuse in the flavor space
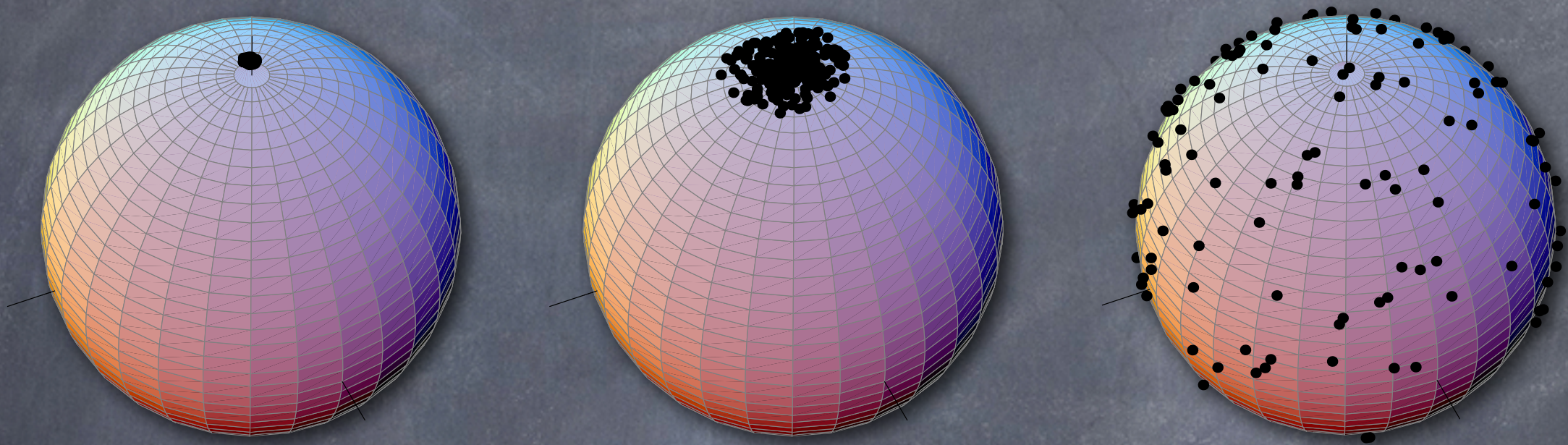
- Need to estimate the rate of diffusion

- Given large-scale fluctuations in published simulations (order 1) and the large measured value of theta13, observable signal expected a few seconds into the explosion

Some technical details

- The level-jumping probability depends on fluctuations

  - relevant scales are small, O(10 km)

  - take large-scale fluctuations from simulations, scale down with a Kolmogorov-like power law

  - contributions of different scales to the level-jumping probability are given by the following spectral integral

$$P \simeq \frac{G_F}{\sqrt{2} n_0'} \int dk\, C(k)\, G\left(\frac{k}{2\Delta \sin 2\theta}\right), \qquad G(p) \simeq \frac{\Theta(p-1)}{p\sqrt{p^2-1}}.$$

for details, see Friedland & Gruzinov, astro-ph/0607244

Neutrino "self-refraction"

- Neutrinos undergo flavor conversion in the background of other neutrinos

- The neutrino induced contribution depends on the flavor states of the background neutrinos

$$\sqrt{2}G_F \sum_{\vec{p}} n_i (1 - \cos \Theta_{\vec{p}\vec{q}}) |\psi_{\vec{p}}\rangle\langle\psi_{\vec{p}}|$$

- One has to evolve the neutrino ensemble as a whole

- Rich many-body physics, with many regimes

Fuller et al, Notzold & Raffelt 1988;
Pantaleone 1992; ...
Duan, Fuller, Qian, Carlson, 2006;
+ hundreds more

ν_e

ν_x

"Beam"

"Background"
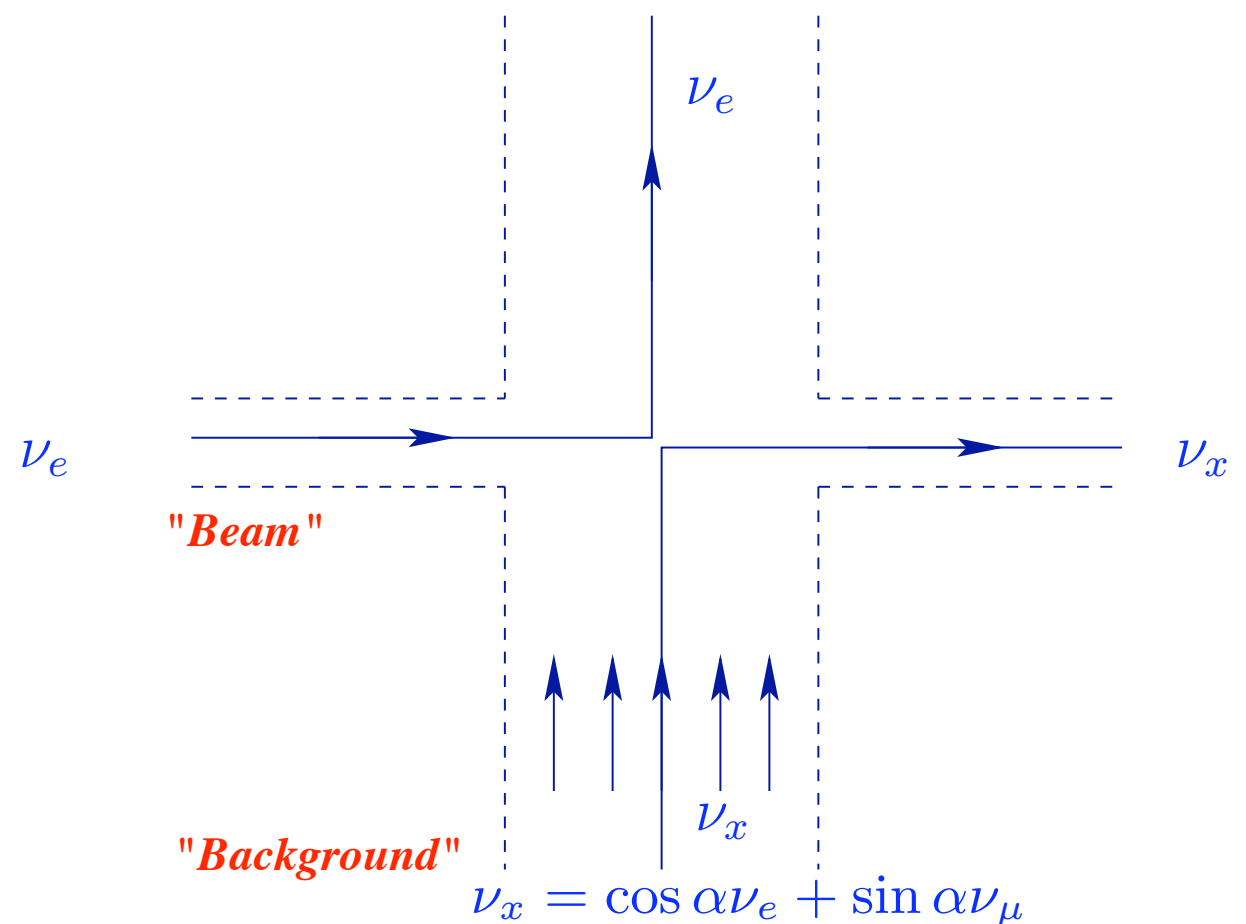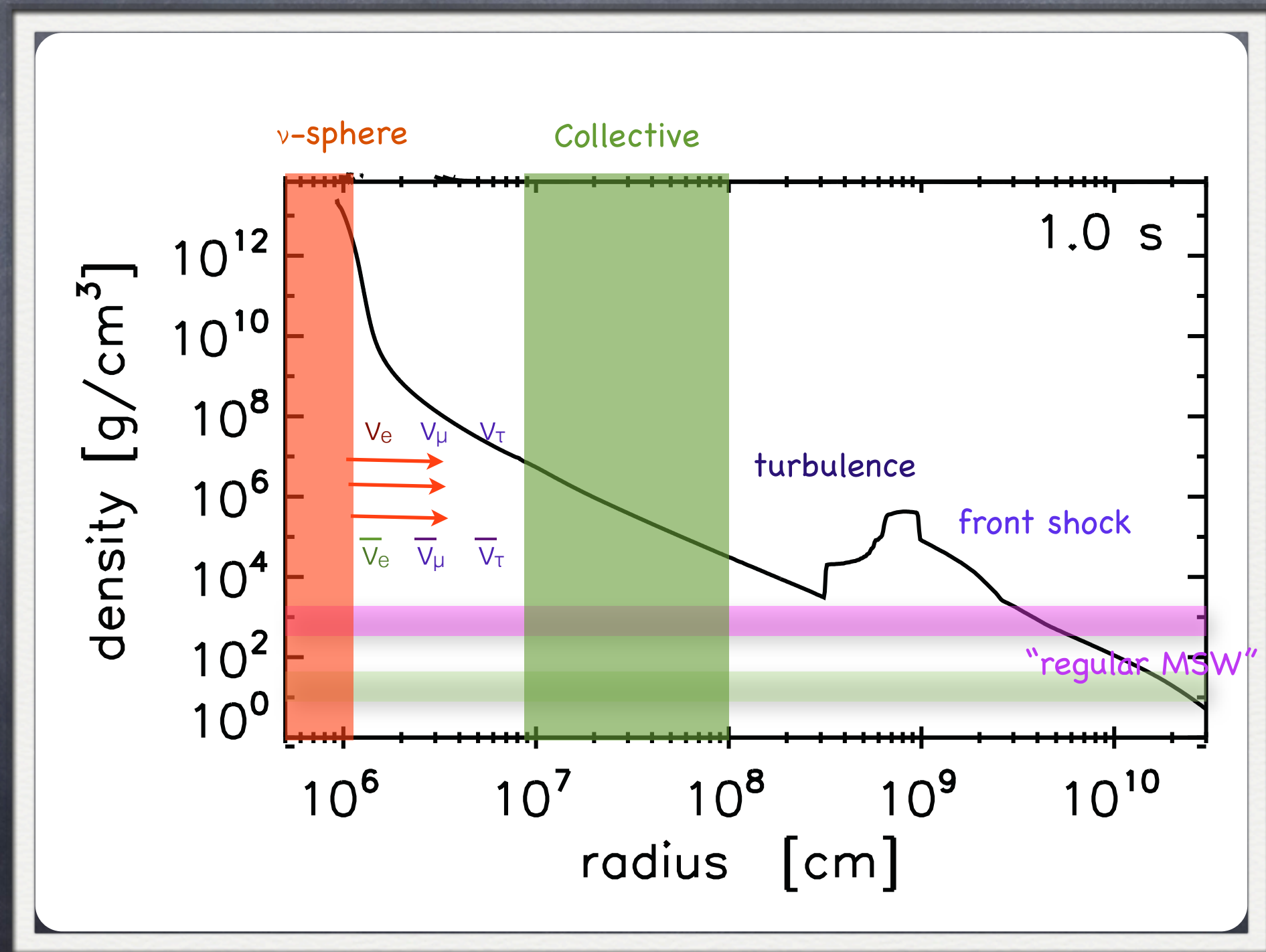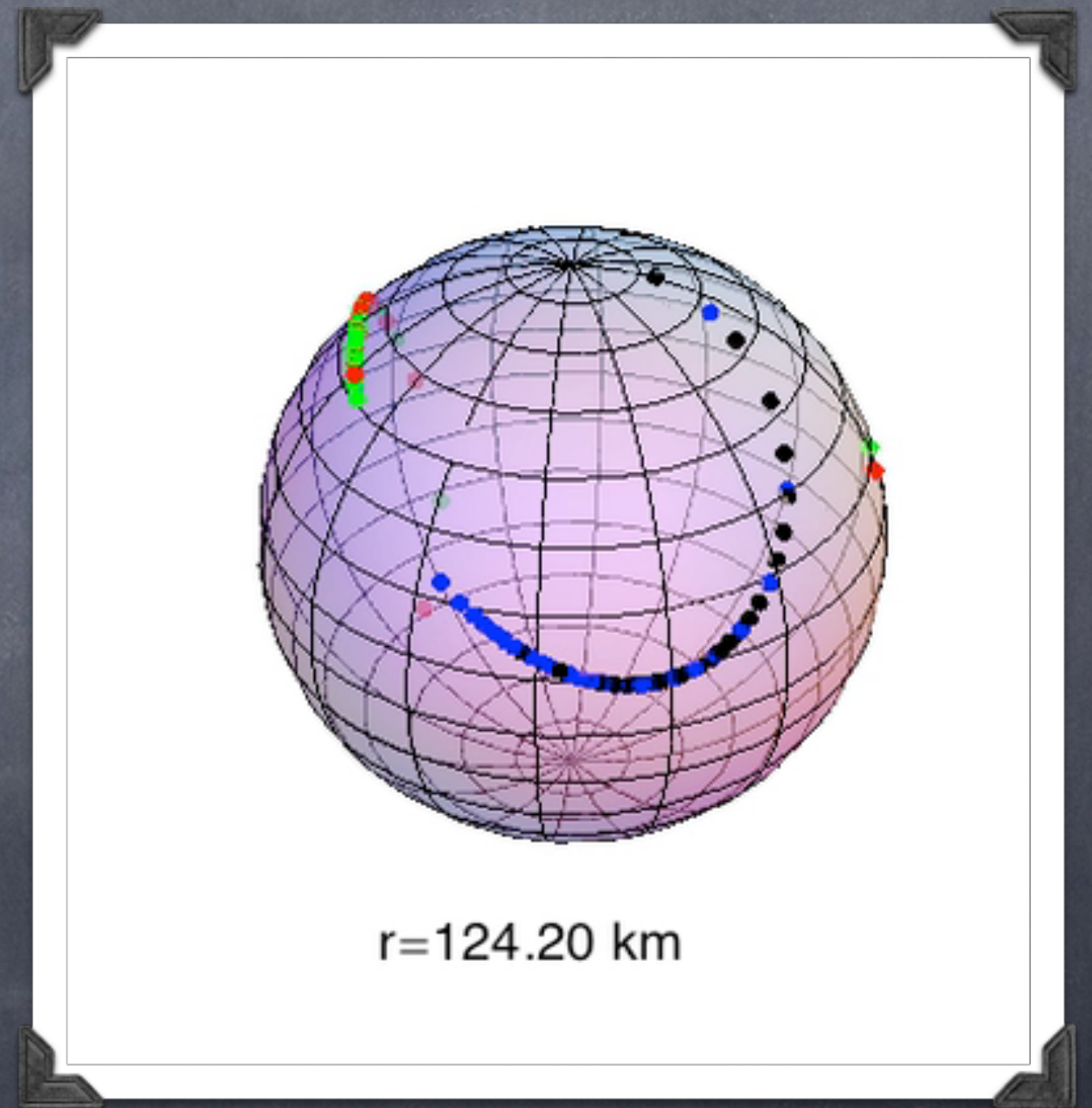
$\nu_x = \cos\alpha\,\nu_e + \sin\alpha\,\nu_\mu$

Figure from
Friedland & Lunardini,
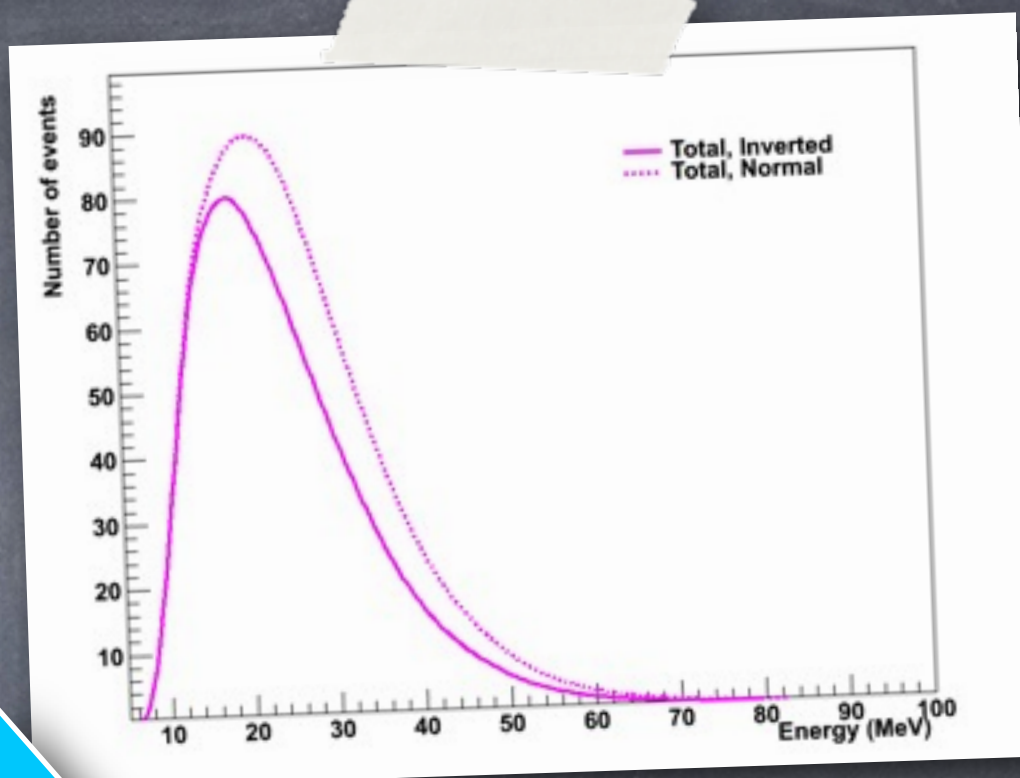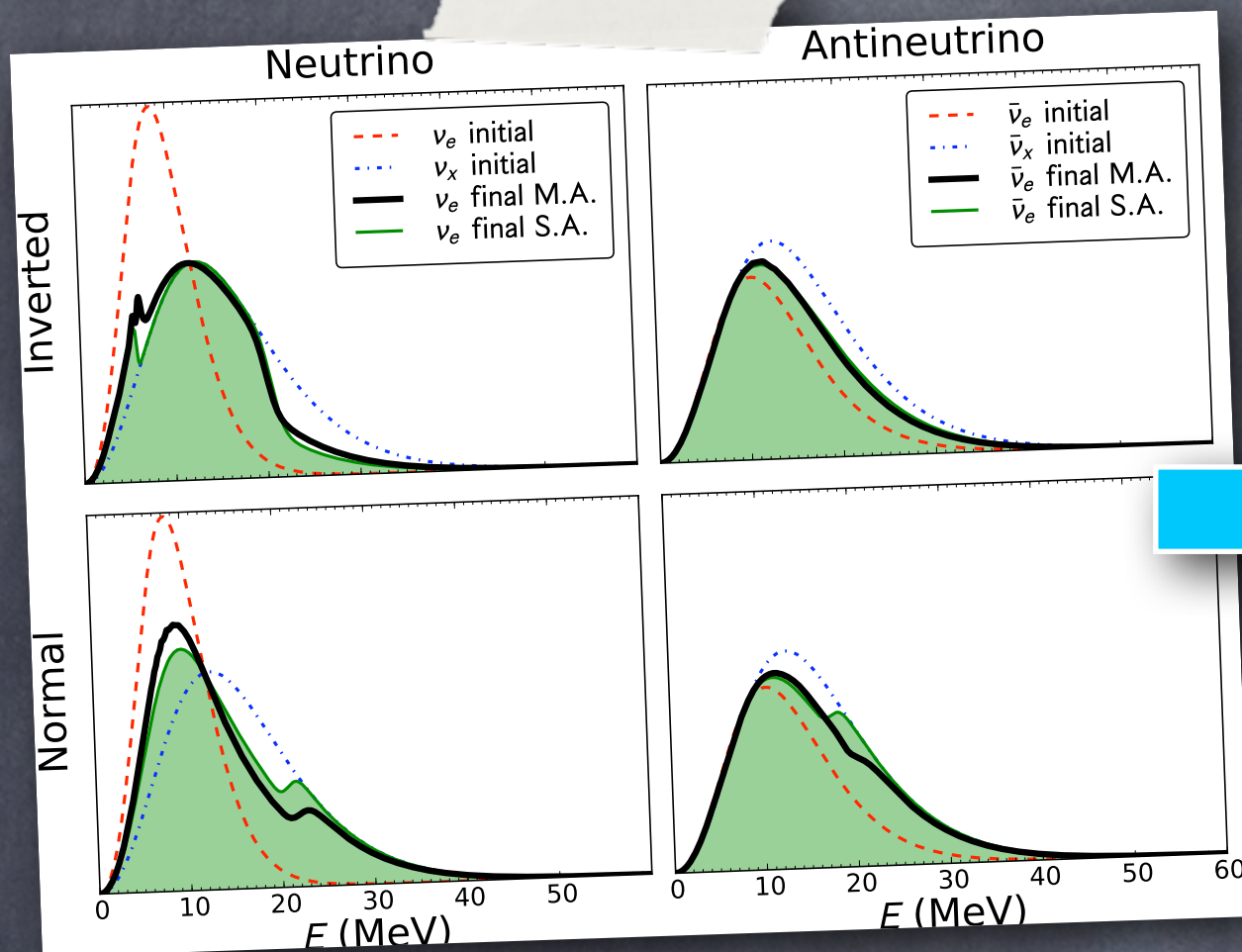Phys. Rev. D 68, 013007 (2003)
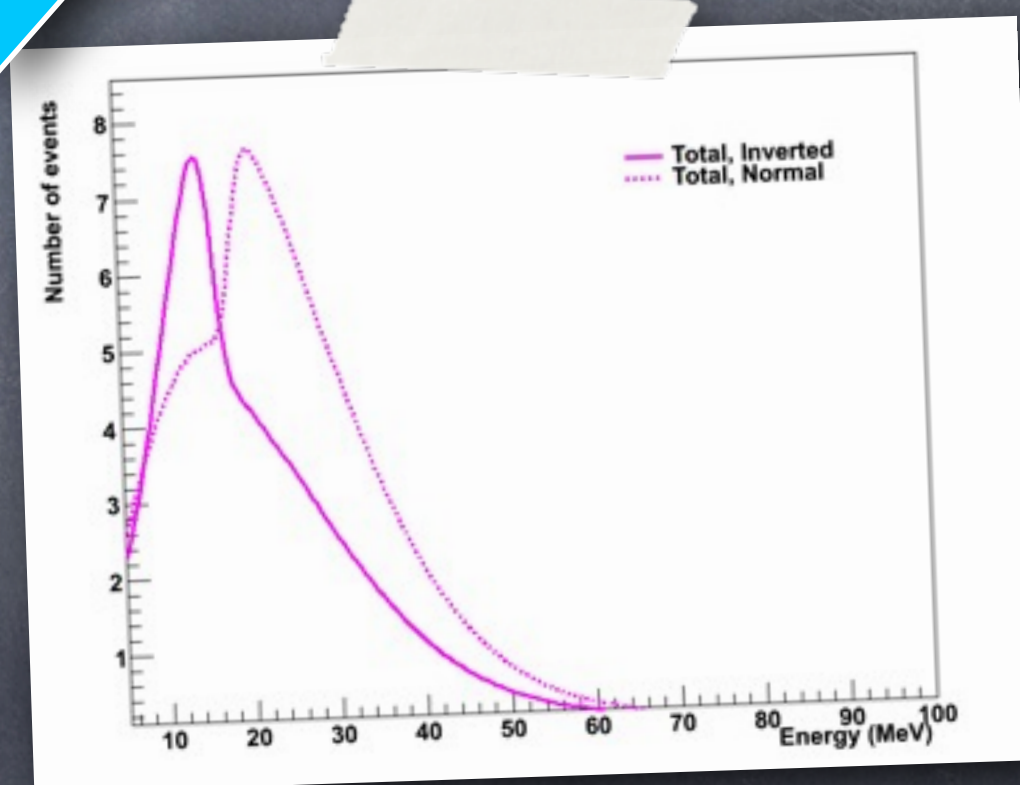
SN ν: summary physics cartoon

Nonlinearity + collective effects at work

- Evolution of the collective mode as a function of radius

- My calculation with

  - two flavors (so that I draw a 3D picture)

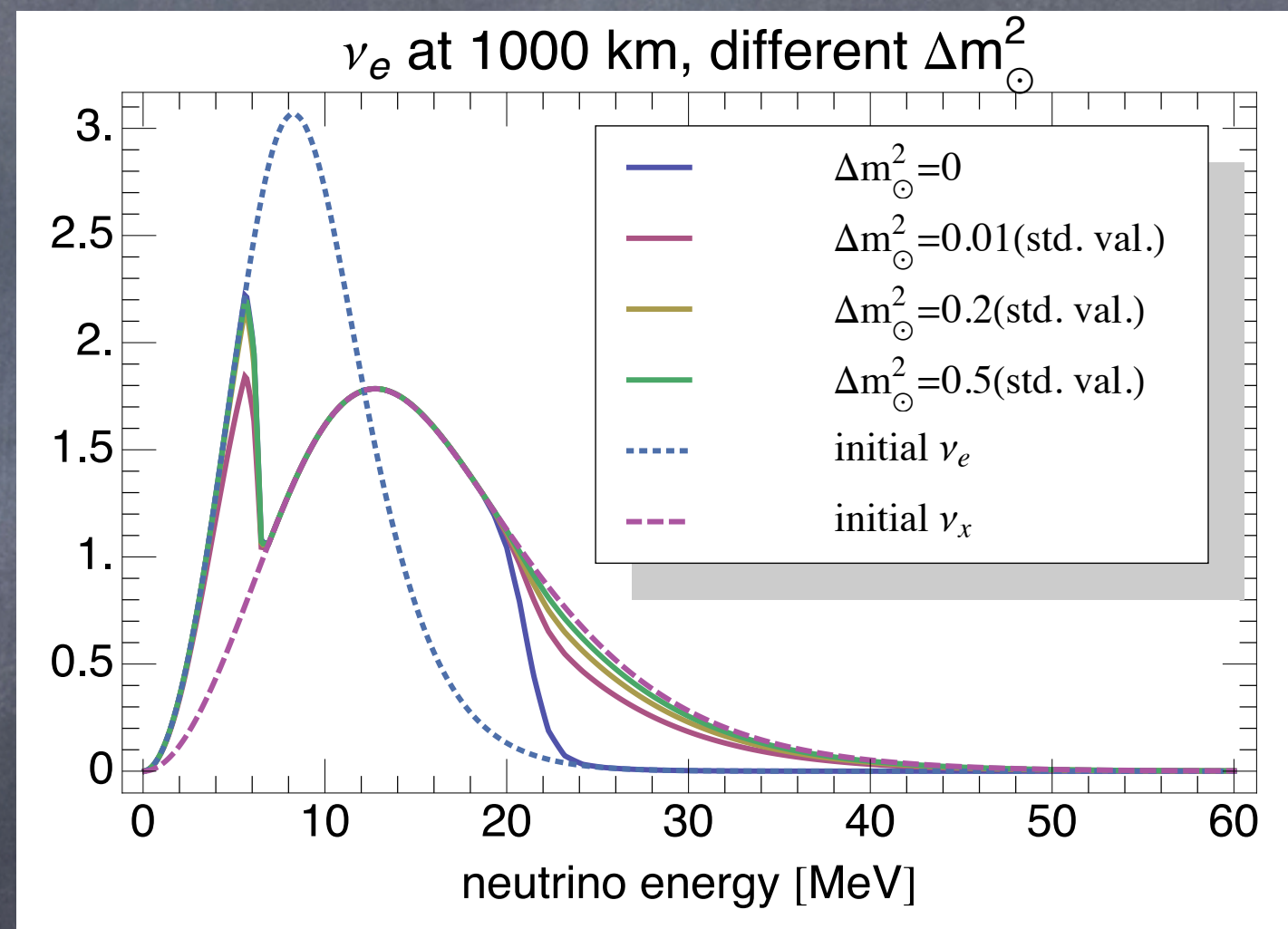 - single-angle approximation (see later)

  - realistic late-time spectra

r=124.20 km

WC

LAr

Neutrino — Antineutrino

Inverted / Normal

ν_e initial
ν_x initial
ν_e final M.A.
ν_e final S.A.

$\bar{\nu}_e$ initial
$\bar{\nu}_x$ initial
$\bar{\nu}_e$ final M.A.
$\bar{\nu}_e$ final S.A.

E (MeV)

Total, Inverted
Total, Normal

* spectra by Duan & Friedland, PRL 2011
* detector modeling by Kate Scholberg & co
* See LBNE physics working group report

Collective oscillations must be done in 3 flavors

- Example where the solar mass splitting is turned on gradually

  - At $\Delta m_\odot^2 = 0$, 2-flavor result is reproduced

  - As soon as $\Delta m_\odot^2 \neq 0$, the answer is closer to the realistic $\Delta m_\odot^2$ than to $\Delta m_\odot^2 = 0$

- 2-flavor trajectory can be unstable in the 3-flavor space

ν_e at 1000 km, different $\Delta m_\odot^2$

Legend:
- $\Delta m_\odot^2 = 0$
- $\Delta m_\odot^2 = 0.01$ (std. val.)
- $\Delta m_\odot^2 = 0.2$ (std. val.)
- $\Delta m_\odot^2 = 0.5$ (std. val.)
- initial ν_e
- initial ν_x

neutrino energy [MeV]

For details, see Friedland, PRL (2010);
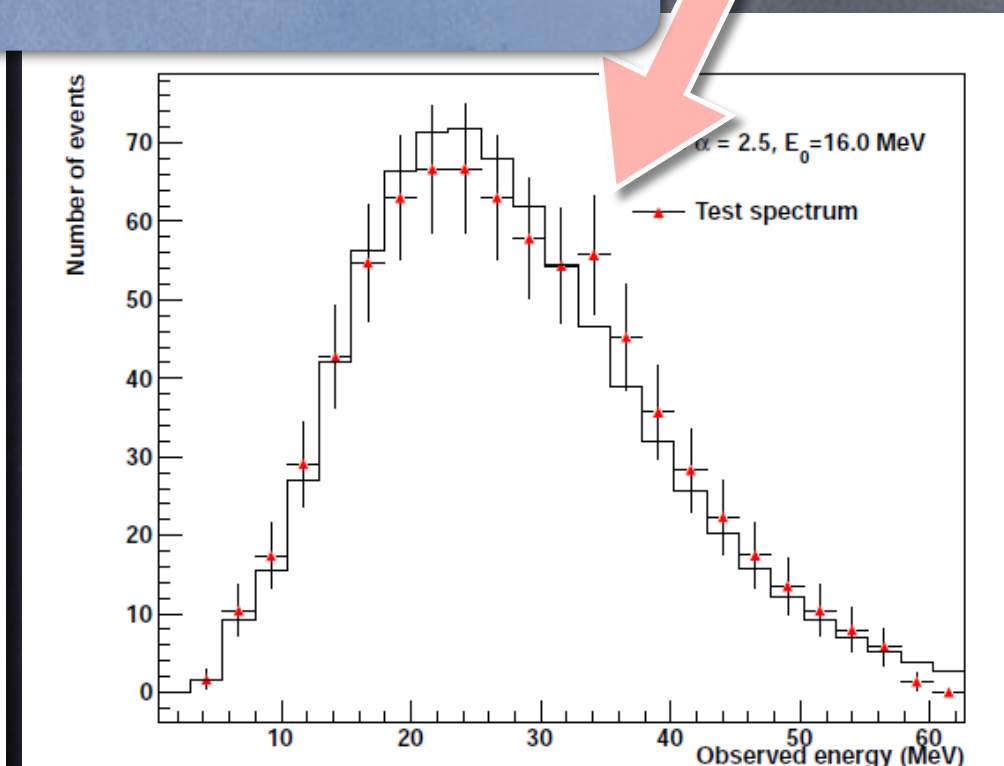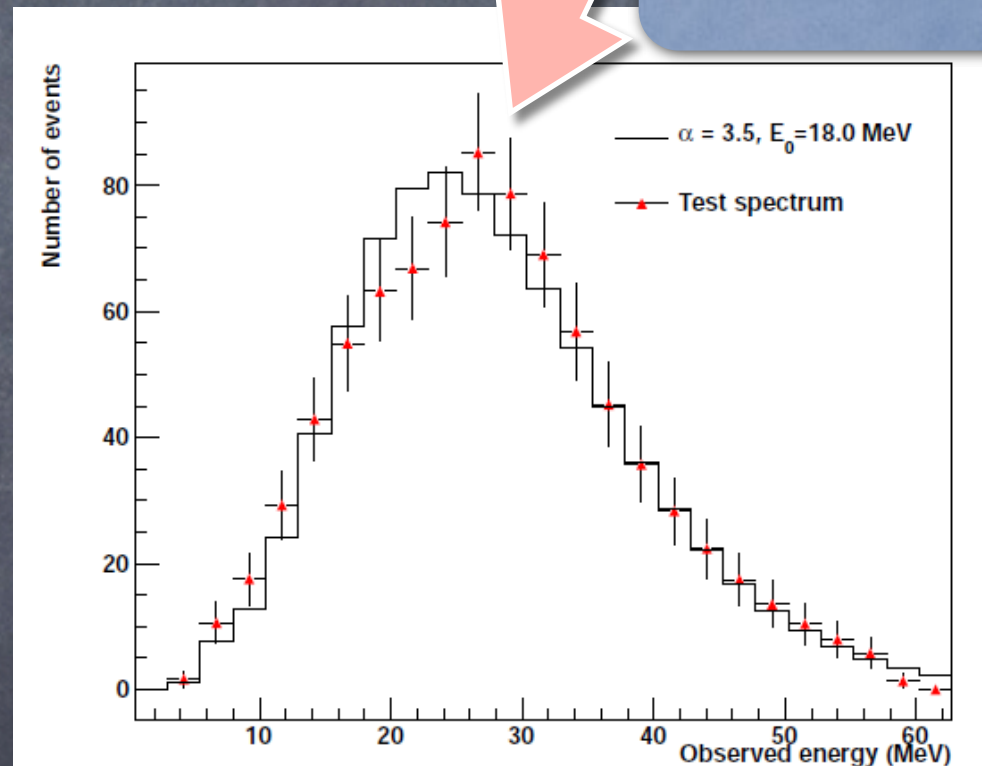also Dasgupta, Dighe, Raffelt, Smirnov, PRL (2009)

What are we looking for? Smoking-gun features

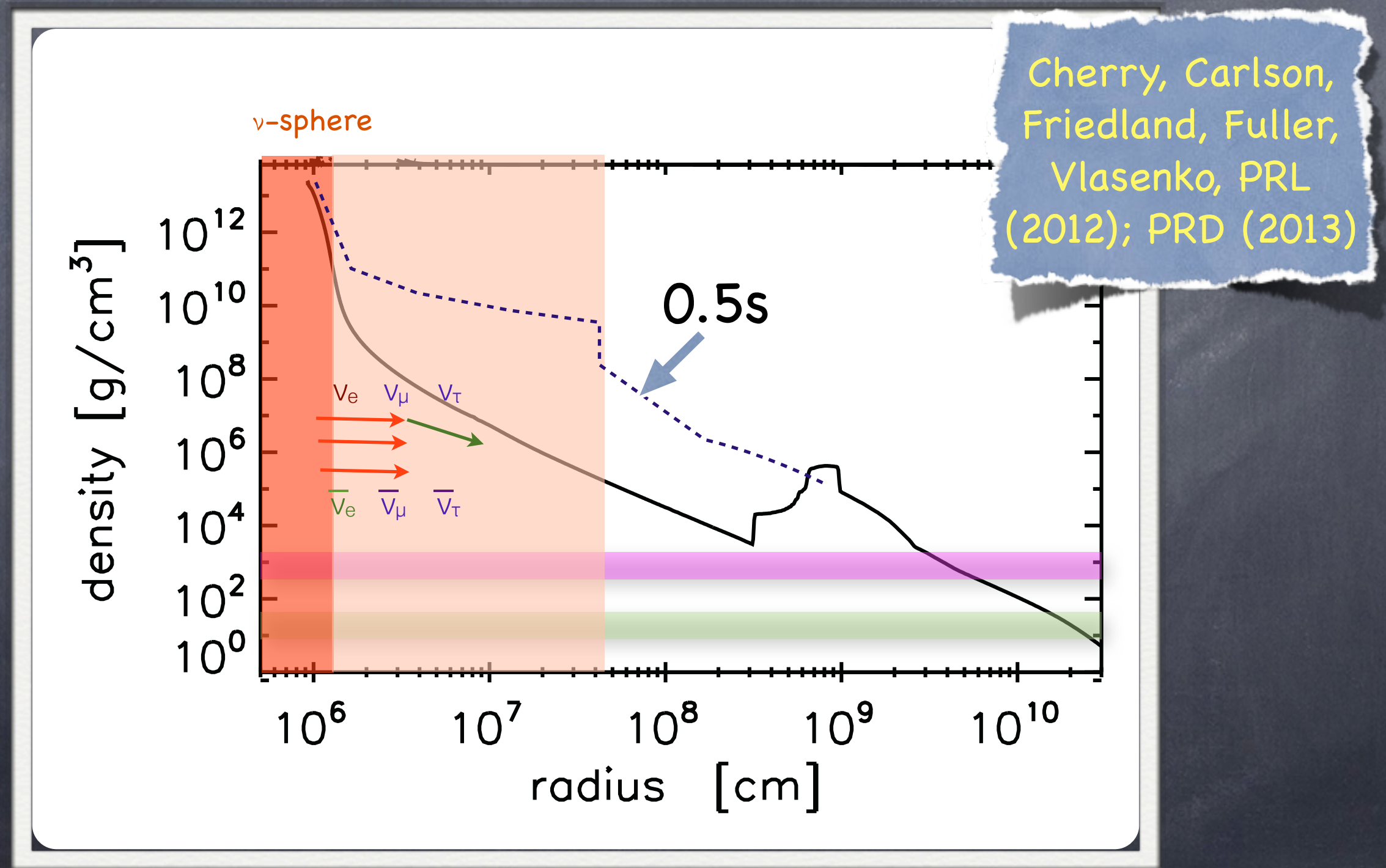Modeling multiangle collective + moving shock by A. F.

Detector model by K. Scholberg

LBNE science document arXiv:1307.7335v3

⊛ The neutrino spectrum is modulated, but not antineutrinos (simultaneously observed by SK/HK)

Accretion phase: neutrinos scattering above ν-sphere?

Much work is still to be done!

- The role of matter in collective oscillations

  - Do they always factorize?

- Dependence of collective transformations on luminosities and temperatures of different components

  - Transition from sharp spectral splits to decoherence

- Breaking of spherical symmetry

  - e.g., Raffelt, Sarikas de Sousa Seixas, PRL 111, 091101 (2013)

- Effects of nonstandard physics

  - e.g., de Gouvea and Shalgar, JCAP (2012, 2013)

P.S. To DOE program management:

Your donations welcome!

Investment of even 5 percent of $10M

could make a world of difference